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Metrics of Human Performance

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Abstract

The purpose of this program of research is to develop metrics derived from multidimensional behavioral and neurophysiological indices which may ultimately be applied across a wide range of tasks to describe and predict human performance. This year's effort represented two different approaches to this problem: the development of a methodology for examining clutter factors that affect target identification, and the evaluation of Catastrophe Theory as a potential metric for describing discontinuities in human behavior.

A comprehensive software/hardware package for examining clutter variables in the laboratory was assembled and its utility demonstrated by a major experiment examining the effect on performance of number of clutter objects and target/drone mix. Initial analysis of the behavioral data has been computed and is reported here. Detailed analysis of the electroencephalographic data is in progress. It is clear that the system provides a powerful, flexible tool for study of visual clutter.

A large representative bibliography of application of Catastrophe
Theory has been compiled and is part of this report. Evaluation of the usefulness of Catastrophe Theory as a metric for predicting human performance
is clear at this time. The theory allows qualitative construction of models
which reflect the behavior of systems in which discontinuities are observed,
but at present does not allow quantative, predictive modeling of such
systems. At present, then, Catastrophe Theory would not seem to be suitable

for generating predictive metrics of human performance.

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I. Introduction:

The purpose of this program of research is the development of a metric or metrics derived from multidimensional behavioral and neurophysiological indices which may ultimately be applied across a wide range of tasks to describe and predict human performance. This might take the form of an "applications handbook" in which the boundaries of human performance are described by these metrics. More importantly, this might take the form of a highly portable test battery which could be used in the field, cockpit, or clinic to provide a rapid evaluation of human performance capability.

The work begun in this year's effort represents two different approaches to this problem: the development of a methodology for examining clutter factors that affect target identification, and the evaluation of Catastrophe Theory as a potential metric for describing discontinuities in human behavior. In this effort, innovative data analysis procedures are being used to reduce behavioral and neurophysiological measures to common metrics of performance. Particular emphasis is being placed on the visual evoked response (VER) as it has become clear in recent years that the VER may be one of the most valuable neurophysiological indicators of performance available to us from the human subject.

All of the goals outlined in the time schedule of the original proposal have been met. The Clutter data collection system has been created and thoroughly evaluated with several pilot studies and a major experiment examining effects on performance of changes in total number of targets and drones and the effects of differing mixes of targets to drones. The survey of Catastrophe Theory is complete and a bibliography of papers relevant to application of the theory to biological systems and performance is part of this report.

II. CLUTTER

Clutter refers to the general problem of identifying a target(s) imbedded in a field of decoys. One practical realization of this is the attempt to confuse an enemy who is trying to shoot down an aircraft by flying a group of drones in the vicinity of the real aircraft. Considerable research has been conducted on radar identification (and confusion) between targets and drones. The present experiment was not concerned with the problem of radar (which may be jammed) but with visual identification with the eye by a ground observer. Visual identification of aircraft has assumed surprizingly large proportions in recent military actions.

The purposes of this year's efforts were: 1) to develop a methodology by which a wide range of clutter factors could be investigated in the laboratory as the first step toward identifying necessary conditions for successful visual protection or identification of target aircraft; 2) demonstrate the usefulness of this methodology by performing an experiment to examine the effects on identification performance of the total number of items (targets and drones) and the mixture of targets to drones; 3) begin to define the functions (metrics) that describe changes in identification performance with the manipulation of clutter parameters.

1. <u>Development of Clutter Methodology</u> - A comprehensive software package was developed for running clutter experiments on the PDP-11/35 in the Visual Display Lab at AMRL/HEA (Wright-Patterson Air Force Base). The hardware configuration for generating the experiment includes a PDP-11/35 computer with 24K words of memory, dual disk drive, 9-track magnetic tape, VT-11 graphics terminal, and LK-40 subject keyboard. Behavioral responses (items identified, latency, etc) were recorded by the computer. Electrophysiological data were

collected from two scalp electrodes (vertex and occipital placements - C_z and O_z in the 10-20 system) referred to left mastoid. These data were amplified by Grass preamplifiers and stored on one inch analog tape. In addition to two channels of data, a third channel was put on analog tape by the computer to mark events such as onset of stimuli and subject responses.

Due to the enormous number of vectors required to create the shape and position of figures on the graphics screen and the heavy computational demands for generating the changes in these vectors that produce the two-dimensional projection of movement in three dimensional space as the clutter "flies" toward the observer, a series of programs were written. In order to have acceptably smooth movement of the clutter objects on the graphics screen, it was necessary to compute all vectors for a complete scenario (from the time the objects appear on the screen until they fly-up to within 0.25 scale miles of the observer) prior to presenting them to the observer. The steps for generating and running an experiment and the programs are described below.

a) Create a parameter file for the experiment

This includes the shapes of the targets and drones, update rate for the graphics display; number of targets in each mix of targets to drones, number of drones in each mix, number of mixes, number of scenarios per experimental block (the subject is given a rest period after each block), and the number of blocks per experiment.

b) Generate Complete Parameter Sets (GENO3)

This program takes as input the parameters in step a) and produces detailed output for generating the specified number of scenarios and blocks with the specified target to drone ratios. This includes permutation of the order of output of the scenarios so the final experiment will be a pseudorandom, evenly distributed presentation of experimental conditions.

c) Generate scenario vectors (F10)

This program reads the output of GENØ3 and generates a file of graphics vectors for each update of the graphics display for the length of the scenario. All of the computation to determine the position of each target or drone in three-space at each update and the mapping of these positions onto the graphics screen is made here. The quantity of data necessary to run an entire experiment of more than about 10 trials with more than about 4 objects on the screen does not fit on the disk. Most of the experiments of interest exceed this limitation, so the data was stored on magnetic tape.

d) Run the experiment (CLUTTR)

This program presents the experiment by reading each update in a scenario into memory for use by the graphics screen. Reading from magnetic tape is too slow, so the program begins each scenario by reading all the updates for that scenario from tape to disk, then reading them one at a time from disk as they are needed to present the moving display. This program records subject responses, latencies of response, and a complete description of the position of the objects on the screen and their scale distance from the subject at time of response. The program also generates pulses to go on analog tape to mark onset of stimuli, subject responses, etc.

1. Pilot Studies: The pilot experiments presented target/drone pairs to 3 subjects for 96 trials on each of 2 days. These pairs were selected from 3 sets of arbitrary shapes in order to determine the ability of subjects to visually detect differences in these shapes. In these scenarios the two objects flew a direct path to the observer starting at a distance of 5 scale miles and terminating with the subject's response indicating he detected a difference, or when the objects were .25 scale miles from the subject. These pilot experiments

provided the means for evaluating identifiability of target/drone shapes and parameters such as ambient room lighting, duration of experimental session, and the like. The pilot data were also used to refine data handling programs at UCLA to facilitate input from the Wright-Patterson system. These experiments led to the selection of delta shapes for targets and drones with only small differences distinguishing them (Fig. 1). Since the purpose of the Clutter methodology is to provide maximum flexibility for laboratory evaluation of many parameters relevant to the entire clutter, it was desirable to keep object cues at a minimum. Therefore, the objects were 2-dimensional with no perspective cues. Even with such a small difference in shape, some subjects quickly became adept at identifying the differences.

3. Experiments: Two experiments were run which manipulated the number of items in the clutter and the ratio of targets to drones in a multidimensional experimental design.

a. Procedures:

Subjects were 4 flight-line and one ground based military personnel. Subjects sat in a darkened cloth enclosure with their eyes approximately 26" from the graphics screen. The graphics screen presented a viewing area of 9" high x 11" wide. The keyboard for responses was located so subjects could rest their hands on it to facilitate making responses. Prior to the start of the experiment, silver/silver chloride electrodes were attached to the subject at the vertex and occipital regions (C₂ and O₂ in the 10-20 system) referred to left mastoid. Impedance between electrodes did not exceed 1.5K ohms. Signals were fed through high-impedance probes into ac preamplifiers (Grass P511) with a bandpass of .1 to 100 Hz. The data then went onto a 1" analog tape (Honeywell). At the start of each scenario the objects were approximately 1/16 in. wide (scale width=50 ft) and at maximum (no subject response to stop the scenario) approximately 1.25 in. (scale distance of .25 miles). Each scenario began at a scale distance of

1000 - 1500 ft. The objects were moving at 450 knots and the direction of movement at the start of the scenario was randomly oriented in the horizontal plane up to 45° from the line of sight between the objects and the observer.

In attempting to simulate realistic flight patterns of targets and drones we have developed a deep appreciation of the myriad factors that must be considered. In an effort to make our simulation as realistic as possible, we contacted the TEDS SPO and asked for advice. They were unable to provide detailed information but made some suggestions. Among these was the requirement that targets and/or drones which approach within 500 feet of each other should make an avoidance turn. Target/drone collisions are avoided by having the drone climb. All objects were to make random turns. Other restrictions on target/drone movement interaction were also suggested.

We began our studies with these constraints and quickly discovered that their statistical properties generate some unusual behavior in the clutter group when there are large numbers of targets and drones (10-20 total objects). The minimum collision path is generated when all objects fly in the same direction. When there is a large number of objects, there are a large number of potential collision interactions if the entire clutter pattern is constrained to a limited-width corridor (say 2-5 miles wide). Very quickly, our simulated clutter tended to align itself so as to fly with minimum collision which causes the aggreate to fly off to one side from the observer's line of sight to the original starting point. The side depends upon which direction most of the objects were moving after making their initial turns. Since collision avoidance is of higher priority than random turns, such turns do not influence the group enough to prevent an alignment to the side for large groups of objects.

Obvious solutions suggest themselves, such as spreading out the clutter so the average distance between object is large. This generates another set of problems since subsets of the overall clutter tend to group and fly off to the side. The constraint which solved these problems was to have all objects fly within a 1 mile wide corridor centered along the line of sight between the observer and the clutter.

To summarize the primary movement constraints:

- 1. All objects flew within a corridor 1 scale mile wide centered on the line of sight between the clutter and the observer. If an object flew out of this corridor, it made a 40° turn toward the center of the corridor.
- 2. When targets approach each other within 500 ft, they made a $10^{\rm O}$ turn away from each other.
- 3. When a drone approaches a drone within 500 ft, they made a 10^0 turn away from each other.
- 4. When a target and drone approach within 500 ft, the drone climbed 500 ft.
 - 5. All objects made 5 random turns of 1°-10° during the scenario.

At the start of a scenario, the subject was looking at a blank screen with his hands resting on the response keyboard. When the scenario began, the objects appeared as very small shapes and began "flying" toward the observer. The subject attempted to identify one target (although more than one may be in the clutter) as quickly as possible. When he had identified one, he pressed any key on the response keyboard. On the display, movement stopped and each object was immediately replaced by a stationary letter located on the screen at the exact location of the object when the response was made. The subject then typed on the response keyboard the letter which corresponded to the object he had identified as a target. After finalizing his choice (striking the return

key) the screen told the subject if he was correct or incorrect and which letters corresponded to targets and which to drones (the letters remain in their position on the screen throughout this feedback). After a 10 sec period, the screen went blank and the intertrial interval started.

If no response was made, each scenario ran about 45 sec. Random intertrial intervals from 5 to 45 sec. separated trials. This experiment presented 55 scenarios per session with a 5 minute break after 30 scenarios. Subjects generally took

1.5 - 2.0 hours to complete a session. Each subject was run in 5 sessions which were spread out over a 3 - 4 week period (availability of flight-line personnel was a prime consideration). Each subject was tested for acuity, depth perception, and ocular muscle balance with the Armed Forces Vision Tester. None of these showed any abnormalities.

Figures 2a-h are photographs of the graphics terminal screen for a scenario (9 targets, 9 drones) with no response. Figure 2a picks the scenario up about 5 sec after it begins. Figure 2h shows the end of the scenario with the 9 targets diving toward the observer. The light images on either side of the group of targets are after images from the graphics screen due to rapid movement of the targets as they dive. This figure is about 38 seconds into the scenario and the targets are between 0.25 and 0.50 scale miles from the observer.

Analyses of behavioral and electrophysiological data from these experiments is in progress. Preliminary analysis of the behavioral data is presented in the following sections. Statistical evaluation has not been completed, but the results reported below were found in at least 4 of the 5 subjects used in these experiments.

b) Experiment I Results:

In this experiment, varying numbers of targets and drones were presented in a randomized order to produce target and drone mixes of 1:1, 1:3, and 1:5. Table I shows the number and ratios of targets and drones used in this experiment. The subjects were instructed to identify a target as quickly as possible. Each subject was run for three experimental sessions of 55 trials each.

In general, there were very few identification errors. Together, all subjects responded correctly to 85.1% of the total of 825 trials. There were only 4 trials (0.48%) on which no response was made before the scenario ended. The data from the relatively few incorrect trials were quite variable, but seemed to follow the same general pattern as correct trials. Therefore, the following analyses are reported for correct trials only with reference made to reliable differences between correct and incorrect trials where they appear. The most pronounced behavioral effects were reflected in response latencies and distance of the identified target from the observer.

There were two response latencies which we examined, the time from onset of the scenario until a key was pressed (to convert the objects into letters - LAT 1), and the time from the first key press until a letter was pressed to identify the chosen item (LAT 2). LAT 1 latencies at least reflect tracking, perceptual identification processes and cognition necessary to make the decision that a target has been identified. LAT 2 at least reflects input and identification of the letters, additional processing of target and drone information from memory and final decision making.

LAT 1 latencies varied considerably on correct and incorrect trials for each subject. However, all subjects had longer LAT 2 latencies on incorrect trials than on correct trials by about 150 msec. This small but significant difference (Mann Whitey U, p < .048) may reflect uncertainty due to differences in the way memory or decision processes operate following perceptual input leading to correct or incorrect responses.

As one would intuitively expect, LAT 1 latencies showed an increase with increasing target/drone ratio (see Fig. 3a). As the number of drones increased relative to the number of targets, the subjects waited longer to make their decision. In addition, there was a trend for response latencies to be longer when there were more total items (targets and objects) in the scenario (Fig. 3b). There was no interaction between these variables, however. Maximum response degradation (longest LAT 1 latency) was obtained for the 1:5 target/drone ratio regardless of the total number of items in the clutter scenario (6, 12, or 18).

LAT 2 latencies showed a substantial increase in response latency with target/
drone ratios of 1:3 and 1:5 as compared to 1:1 (Fig. 4a), and there was a very clear
increase in response latency as a function of increasing total number of items
(targets plus drones) (Fig. 4b). These latencies also increased as a function of
increasing number of targets. LAT 2 latencies were generally longer when large
numbers of drones were present as compared to lesser numbers of drones but the
function is not as nicely linear as for the total number of items and number of targets.

LAT 1 latencies are roughly correlated with the final distance of the targets and drones from the observer when he makes his response. In general, the longer the LAT 1 time, the closer the targets and drones to the observer. Due to the

flight patterns and interactions between targets and drones, the final distances cannot be accurately predicted from the LAT 1 latency, and an analysis of the distances of targets at the moment of response was made.

In agreement with LAT 1 changes by target/drone ratio (Fig. 3a), distance of the selected target and mean distance of the group of targets as a whole decreased with increasing target to drone ratio (Fig. 5 solid line). That is, the fastest responses (shortest latencies) were made when the target/drone ratio was 1:1. A short latency implies the object has had less time to travel toward the observer and should be further away at the moment of response. This is verified by Fig. 5. The dotted line in this figure shows themean distance of all the targets at the moment of response. It is clear that the subjects responded to targets closer to them than the average, especially when the clutter was further away (l:1 ratio).

Distance of the selected target from the observer is less than the mean distance of all targets as a function of the total number of items in the scenario (Fig. 6). This is especially pronounced for large numbers of items (6 or more). With only 2 items there is one target and one drone so both the selected and the mean of all targets is the same point. It is interesting that for large numbers of total items in the scenario, the subjects wait to make their response until a target is very much closer than the mean target distance.

Upon examination, our data appeared most consistent for trials on which there was only one target. Figure 7 shows LAT 1, LAT 2 and the target distances for all one target trials as a function of total of items in the scenario. Compared to the means for all targets, one target trials show longer LAT 1 values at 4 and 6 items (2 items are the same for both sets of data), shorter LAT 2 values and smaller

distances. The next experiment was run to further examine the one target scenario with additional numbers of drones to see if a point of maximum response degradation (maximum long latency) could be found.

c) Experiment II - Results:

This experiment was very similar to Experiment I except that only one target was paired with 1, 3, 5, 7, 11, and 15 drones (see Table I). Subjects for this experiment were the same as for Experiment I. Each of them was given two experimental sessions of 90 trials each. There were relatively few errors as subjects correctly responded to 83.2% of the total of 900 trials. There were 14 trials (1.56%) on which no response was made before the scenario ended.

As in Experiment I there was an increase in LAT 1 latencies with increasing total items in the scenario (Fig. 8a). LAT 2 latencies showed a similar but less consistent change as a function of total items (Fig. 8b). The mean distance at which the target was identified decreased as the number of drones increased (Fig. 8c).

In comparison with the 1-target data from Experiment I (Fig. 7), the curves for LAT 1 and LAT 2 are very similar. Exp. II LAT 1 values are shorter and LAT 2 values longer than in Exp. I. Distance of selected targets does not monotonically increase over the whole range of numbers of items, but shows clearly decreasing distance with increasing total number of items in the scenario. Target distances in Exp. II are longer than distances in Exp. I. The addition of items 8, 12, and 16 in Exp. II does not substantially alter the trends observed for items 2, 4, and 6 in Exp. I. There is the possible suggestion that LAT 1 and LAT 2 values may have reached their peak at 12-16 elements and that adding additional

drones would not produce the same nearly linear changes observed below that number.

Only additional data can determine if the rate of increasing latency in fact does slow down at this point.

4. Summary and Conclusions

We have developed a powerful research tool for the laboratory study of a wide range of clutter factors. The usefulness of the system has been demonstrated by experiments examining the effects of number of scenario elements and target-drone mix on identification of targets. Preliminary data analyses are summarized below.

The time from first sighting of a clutter to an initial response identifying a target (LAT 1) along with the distance of the target from the observer, are the data of greatest practical interest in the clutter situation. Initial analysis of the behavioral data suggests that, for the ranges investigated, the ratio of targets to drones, regardless of the total number of drones, has the largest effect on identification response time (LAT 1). The more drones per target, the more difficult identification of the targets becomes (longer response times). The total number of elements in the clutter affects the response time also, with longer response times associated with increasing numbers of elements. Interestingly, these two variables do not interact, so there is no advantage (or disadvantage) to using a large number of targets and drones in a given ratio rather than a small number of targets and drones in the same ratio.

These changes in response times are reflected in the distance of the target from the observer. Observers wait until targets are closer before identifying them

as the number of drones per target increases and as the total number of items increases. This confirms the intuitive notion that any attempt to design flight scenarios using drones to interfere with visual identification of piloted aircraft should consider large numbers of drones per target, for few or many targets, for maximum effect.

Over the range of targets and drones examined, we found no indication that maximum interference was being produced. Additional experiments would be necessary to determine at what point increases in target/drone ratio no longer produce significant performance decrements. The second experiment we ran approached this question of limits by pairing only one target with up to 15 drones. This one target experiment found the same trends reported above. However, there was the suggestion of a flattening of the increasing response times for scenarios in which the target was paired with 15 drones. Additional research would be necessary to verify that this represents a leveling off of the performance decrement.

After the initial response signaling that a target had been identified, a second latency was measured from the time of the first response until a key was pressed identifying which clutter element was chosen (LAT 2). If subjects were definite about their choices at the moment of their initial response, this second latency should merely reflect time to select the correct key and press it, and this latency should not differ significantly over experimental conditions. There are, however, substantial differences as a function of total number of items and number of targets, and a trend for target/drone ratio. This suggests significant cognitive activity, probably involving processing from memory, after initial selection of the target.

While this experimental design did not allow the scenario to continue moving toward the observer after he made an initial response, one might speculate that if a direct movement had continued until a final response was made, subjects may have taken longer to make a decision, allowing the targets an even closer approach, when there were many drones per target or many total items. This possible ongoing cognitive activity may be reflected in the EEG analysis we are doing to provide a key for predicting degradation or enhancement of identification performance.

Latencies were generally shorter (and target distances longer) in Exp. II than Exp. I. This could have been a practice effect since Exp. II immediately followed Exp. I. Trends in both experiments were the same however, and support the finding that increasing the number of drones per target interferes with target identification.

It is obvious that increasing the number of irrelevant items (drones) increases the noise in which a signal (target) must be identified. One way of categorizing this is in terms of the information available to and provessed by the observer.

We are currently performing an information theory analysis on these behavioral data to examine the way in which our subjects acted as data channels to process the information available in the clutter display. The usefulness of these measures as metrics for predicting performance is being evaluated as the data is analyzed.

Our unique combination of data collection and analysis techniques, for behavioral and electrophysiological data, developed for this effort will be part of a paper I have been invited to submit for a special issue of the Brain Theory Newsletter titled, "Computers in the Neuroscience Laboratory", to appear in the fall of 1978.

III. Catastrophe Theory

Scientists have long used mathematical models to describe events in the real world. The most often used mathematical techniques have been those which describe smoothly changing, continuous phenomena, differential equations being perhaps the best known example. Unfortunately, psychologists, physiologists, and social scientists (among others) are daily faced with phenomena which are not continuous and for which existing mathematical techniques have not been effective.

Considerable excitement, therefore, has attended the recent appearance of Catastrophe Theory, developed by the French mathematician Rene Thom (1972). Derived from the field of topology, this theory provides a framework for the description of situations in which a continuous change or perturbation of control variables leads to a discontinuous change of outcome. The theory has been acclaimed for its potential application to real problems in morphogenesis, linguistics, gas dynamics elasticity, brain function, economics, sociology and other fields (see Hilton, 1976 and Zeeman, 1976a). The term 'catastrophe' is due to Thom and is not intended to carry the connotation of a disaster, only of a sudden, noncontinuous change.

Catastrophe theory may provide the basis for quantitatively modeling aspects of behavior which have long been of vital importance to Air Force operations. One such application is the modeling of sudden discontinuties (breakdowns) in performance of goal-oriented tasks such as piloting an aircraft under variable, changing information load and stress conditions. In many such situations no effective mathematical models have been developed which satisfactorily predict the breakdown of performance or suggest the means for avoiding that breakdown.

The purpose of this review is to evaluate Catastrophe Theory as a potential metric for predicting human behavior. This survey is not intended to be a

comprehensive review of all published material and the treatment of the matematics of the theory is beyond the scope of this effort. Good bibliographies on the mathematical basis for the theory and early applications may be found in <u>Dynamical Systems</u> (A. Dold and B. Eckmann (eds.), Berlin, Springer-Verlag, 1974) and Hilton (1974). These sources contain numerous foreign language (non-English) references not included here. This survey is meant to compile and evaluate a substantial representative sample of the applications of Catastrophe Theory to biological, behavioral, and physical systems. By applications is meant the attempt to model some real system with the mathematics of Catastrophe Theory, even if only a qualitative graphical description resulted. While description of behavior is very useful, the key for practical application of a metric is its ability to predict. This evaluation places particular emphasis on the applications of Catastrophe Theory which demonstrates its predictive capability.

1. What is Catastrophe Theory?

The founder of this branch of mathematics, Rene Thom, has called it a language, not a theory in the usual sense. It allows one to classify and display underlying patterns. He also asserts that it is qualitative rather than strictly quantative even though quantative measures are derived from it. Recently Thom (1977) has said, "The truth is that C.T. (Catastrophe Theory) is not a mathematical theory, but a 'body of ideas', I dare say a 'state of mind'". Some of the more enthusiastic have called it an "intellectual revolution" equivalent to the development of the calculus (Parati, 1976).

The theory is derived from the field of topology which is the branch of mathematics which deals with properties of surfaces in many dimensions. The so-called behavior surfaces generated by the mathematics are called manifolds and are essentially solutions to equations called energy functions. These functions describe systems which tend toward

minimum potential energy. These minima are places at which the system is in equilibrium and are shown as points on the surface of the manifold.

Thom's most elegant finding is that if a situation can be described by an energy function, if the change in control parameters is smooth and continuous, and if there are no more than four control parameters, then there are only 7 elementary catastrophes that can occur. By increasing the dimension of the control space, infinite lists of catastrophes can be constructed. It is reported that the Russian mathematician, V. I. Arnold, has classified them up to at least 25 dimensions.

The seven elementary catastrophes are graphically depicted in Figure 9a-g. The fold and cusp catastrophes are the only ones that can be drawn in their entirety. For the next three higher-dimensional catastrophes, only the three-dimensional bifurcation sets can be drawn (the bifurcation set is the projection in three-dimensions marking when the behavior becomes bimodal). For the final two catastrophes, bifurcation sets have more than three dimensions and they may be shown only in sections.

The most commonly used catastrophe is the cusp which results from a control space of dimension 2. As an example of the cusp catastrophe, Zeeman (1976a) has described the now often quoted model of aggression in the dog. We report this example directly from his Scientific American article. In this model of aggression in the dog, rage and fear are assumed to influence aggressive behavior. Rage is measured by the degree to which the dog's mouth is open and teeth bared, and fear is measured by how much its ears are flattened back. If only one factor is present the behavior is easily described. If the dog is enraged, but not afraid, some aggressive action can be expected. If the dog is frightened but not enraged, fleeing activity is expected. If neither is present, neither aggression nor fleeing is expected.

If rage and fear are present simultaneously, these control factors may be plotted as axes on a horizontal plane called the control surface. The behavior of the dog from attack to retreat is represented on a vertical axis For any point on the control surface there is at least one likely form of behavior represented as a point on the vertical axis above the corresponding point on the control surface. The set of all such points makes up the behavior surface. Where rage and fear are roughly equal, there are two probable modes of behavior, attack or retreat, represented by the two sheets in the middle of the graph. The middle sheet connecting the two other surfaces represents the least likely behavior and in fact cannot be reached. Toward the origin, the pleat in the behavior surface becomes narrower and eventually vanishes. The lines defining the edges of the pleat are called the fold curve and its projection onto the control surface is a cusp-shaped curve from which this catastrophe draws its name. The cusp marks the boundary where behavior becomes bimodal. If an angry dog becomes more fearful, its mood follows trajectory A on the control surface. The corresponding path on the behavior surface moves to the left on the top sheet until it reaches the fold curve where the top sheet vanishes and the path jumps abruptly to the bottom sheet. Similarly, a frightened dog that is angered follows trajectory B. A dog that is angered and frightened at the same time must follow one of the two trajectories at C. Whether it moves onto the top sheet and becomes more aggressive or onto the bottom she'et and retreats, depends critically upon the initial values of rage and fear.

As another example of the cusp model (Zeeman, 1976a), Fig. 11 shows the behavior of an elastic beam under the control of load and compression forces. If the beam is flat, an increase in compression forces it to buckle upward or downward. If it buckles upward, a subsequent increase in load drives the control point across the cusp, causing a catastrophic downward motion.

2. Application of Catastrophe Theory

The number of reports of Catastrophe Theory applications have grown as the theory has gained widespread public exposure from descriptive articles appearing in a range of publications from Newsweek (Parati, 1976) to The Sciences (Gorman, 1976). It seems that the theory has become in vogue scientifically with the expected number of radical proponents and opponents.

Thom's concern in developing this theory was to provide a mathematical framework for the description of natural phenomena. He envisoned that this framework should be applicable wherever mathematical models are appropriate in scientific study. In Thom's formal presentation of the ideas of Catastrophe Theory (1972) he suggested a wide range of potential applications from biology to sociology to physical systems.

The application of Catastrophe Theory is delicate and solid applications can be made only when appropriate control parameters, behavioral variables and the potential energy functions have been identified and matched to the problem (Gorman, 1976). Dr. Christopher Zeeman (1974) has suggested that Catastrophe Theory models may be appropriate if systems exhibit bimodality, divergness, catastrophic jumps or hysteresis delays. A partial list of his attempted applications of the theory includes models for:

1)	sensory input	(1977)
2)	association	(1977)
3)	recal1	(1977)
4)	aggression	(1976a)
5)	anorexia nervosa	(1976a)
6)	manic depression	(1973)
7)	self-pity	(1976a)

the stock market

(1976c)

- 9) phase transitions between liquid and gaseous states of matter (1976a)
- 10) stability of ocean going ships (1977)
- 11) prison disturbances (1976)
- 12) effects of stress on speed estimation (1976b)
- 13) heartheat and nerve impulse models (1971)

Specific applications by other investigators include models for:

- 1) changes in blood plasma volume (Wilkerson, Gutin & Howarth, 1977)
- 2) Animal morphogenesis (Cooke and Zeeman, 1976)
- 3) Geological processes (Henley, 1976; Cubitt and Shaw, 1976)
- 4) Visual system (Koenderink and Von Doorn, 1976)
- 5) Cellular differentiation (Woodcock, 1974)
- 6) Evolution (Waddington, 1974)
- 7) Manufacturing imperfection and structural strength (Thompson, 197
- 8) Spatial organization in early animal development (Cooke, 1975)

For several reasons, most of the applications reported in the literature deal with the cusp catastrophe. It is the highest-order catastrophe that can be drawn in its entirety in three dimensions, it deals with only a two dimensional control span (considerably simplifying the computational requirements for generating the surfaces) and it is generally more interesting than the one-dimensional fold catastrophe. A final compelling reason seems to be that most of us are able to think more clearly in three dimensions than in four or more. Though few in number, there have been reported applications of the other dimensioned catastrophes. Some examples are the fold (describing blood plasma volume, Wilkerson, Gutin, and Horvath, 1977), the butterfly (describing cellular mutation, Woodcock, 1974), and the hyperbolic umbilic (analysis of manufacturing imperfections, Thompson, 1975).

As reflected in the listings above, Catastrophe Theory has most often been applied to biological and social problems. However, the strengths and weaknesses of the applications seem about the same whatever the field of application. Examples of cusp models from all disciplines are virtually of the same form. Examples of higher-order catastrophies produce different pictures but not fundamentally different information.

A few representative models will be briefly described below.

- A. Henley (1976) discusses several cusp models applicable to geology. He describes how to set up a model of fault movement with friction and shearing energy as the control variables and the rate of movement as the response variable. At low values of friction, only a small amount of strain energy is needed to initiate movement and movement will increase with increased energy. At high friction values, energy increases will not cause any movement until some threshold value is reached. At this point there will be a sudden jump to high rates of movement. If energy is now released (as it is in an earthquake), there will be a jump back to zero movement.
- B. Thompson (1975) has applied Catastrophe Theory concepts to highly optimized engineering structures. He examined the elastic buckling of an optomised stiffened panel similar to those used in box-girder bridges. His model was compression by an axial load, parallel to the stiffeners. The two possible failure modes are deflection, like the buckling of a beam described earlier, or rippling when the material between stiffeners becomes deformed. By simulating an initial deflection representing a manufacturing defect, he obtains an imperfection-sensitivity curve which is characterized by a sudden dynamic change in the range of material elasticity. An extension of this analysis by V. Tvergaard and G.W. Hunt (unpublished) to give the complete imperfection-sensitivity surface yields a hyperbolic-umbilic catastrophe a portion of which describes panel strength.

C. Woodcock (1974) generally describes the use of Catastrophe models for describing cellular differentiation. In the urfertilized egg, the enzymatic manufacturing mechanisms probably support only a few of its many possible reactions because the egg is excluded from the external environment by its relatively impermeable cell boundary. In the fertilized egg, the cell boundary becomes permeable, the concentrations of enzymes inside the egg change drastically as the outside environment is contacted and biochemical reactions move away from their original equilibria to approach other states.

This state of affairs may be modeled as a catastrophe manifold in which there are many control parameters (biochemical reactions) guiding embryonic development. The state point describing the changing cell is free to move about the catastrophes manifold and it may move into a region of the space in which more than one stable state or more than one type of biochemical reaction scheme is possible. In the latter case, bifurcation between types of biochemical reactions may occur. The bifurcation may occur in either of two ways: 1) the cell might adapt different biochemical reactions (slowly) without any discontinuities, and 2) different regions of the cell might approach different reaction equilibrium conditions leading to development of a shock wave which would trigger the fission of the cell in two. The resulting Catastrophe manifolds are not easily described in terms of the seven elementary catastrophes. Some of them have the appearance of a double cusp or a butterfly catastrophe with cusplike projections.

It is pointless to present further examples since they all can be summarized by saying that catastrophe theory provides a description of the observed process, but that there are no clear applications in which quantative or non-obvious qualitative predictions have been made. This evaluation is shared by Henley (1976). At the very outset (paragraph 2) of his paper, Henley firmly delimits the usefulness of Catastrophe Theory. "Catastrophe Theory is a development in differential topology which allows the qualitative construction of models which mirror closely the behavior of natural systems in which discontinuities are observed, although at present it does not allow quantative, predictive modeling of such systems."

"... it is hoped to show that catastrophe theory may provide useful formulations of such phenomena which could eventually lead to the generation of models which, if not predictive, at least add to geological insight and understanding in the same manner that catastrophe theory is assisting the biologist" (pages 2-3).

One of the more successful applications in which some limited predictive utility was realized was the application of a fold catastrophe to changes in blood plasma volume (Wilkerson, Gutin, and Howarth). Their model accurately predicted changes in plasma volume in a narrow region around the catastrophic break but showed considerable error elsewhere. The authors believe this is a result of errors due to insufficient data, not from a failure of the model. However, as they point out, the model requires a hysteresis about the break which would have to be substantiated for verification.

There have been a number of claims that catastrophe models have provided new insight and prediction. Zeeman (1972) presented a model for heart-beat and nerve impulse that he compared to the classical equations of A.L. Hodgkin and A.F. Huxley. Of the list of predictions which follow from his

model, Zeeman claimed in 1976 that experiments have confirmed some of the predictions. Sussman and Zahler (1977), in their criticism of Catastrophe Theory, point out that no experiments have actually been done to test these models (Zeeman confirmed this in a letter to those authors) and the experiments Zeeman cited are not viewed by the researchers who performed them as support for his model.

In general, Zeeman's attempts to apply catastrophe theory to neurophysiology can be criticized on the grounds of naive and incomplete assumptions about the function of brain tissue. His naive discussion of the role of the limbic system and its role in mood and anorexia nervosa (1976a,b) seriously compromises the assumption for any modeling attempt. Simplifying assumptions are an important and useful part of mathematical modeling which is justified if the models produce new insights about the phenomena they mimic. At this time no new insights or verified predictions have yet evolved from catastrophe theory models of neurophysiology.

Sussman and Zahler report other exaggerated claims for catastrophe theory. "A brochure describing the 1977 Encyclopedia Britannica Book of the Year announced that the book contains an essay by Ian Stewart of the University of Warwick on catastrophe theory, ... a stunning mathematical theory that is being applied to help predict accurately a number of natural situations (earthquakes and floods, the ups and downs of the stock market) and human situations ... '. The truth is that no application exists which makes any predictions whatever about earthquakes or floods".

A summary of criticisms by Sussman and Zahler appeared in Science (Kolata, 1977). That summary focused on what is claimed to be a misuse of mathematics, false reasoning, and ambiguous language used by proponents of the theory (primarily Zeeman). This article gave rise to a number of letters to the editor

in which the overwhelming theme is that it is unfortunate that such extreme positions have been taken by those for and against the theory.

Thom (1977) presented his reservations on the suitability of applying catastrophe theory to real data. His objection stems from the fact that (especially in 'soft'areas such as sociology) the homogenity requirement for the data is generally not satisfied for the modeled phenomenon. If this requirement is not met, it is not possible to reliably expect the derived functions to be invariant with respect to space dialation. If this is so, the functions will have expressions which will arbitrarily depend upon the units used to measure the magnitudes entered into the formula. He feels the procedure of fitting a catastrophe scheme to empirical data is no more reliable than any other approximation procedure of numerical analysis (such as interpolation of a continuous function by a polynomial by the least squares method), and its validity should be confirmed in each case. "... obviously we cannot expect such approximating devices to throw any light on the mechanisms underlying the studied phenomena". (Thom, 1977, p. 196)

It is our assessment that the excited emotionalism that breeds these controversies is dying down. Catastrophe theory is being used cautiously in new applications (see quote from Henley above) and more attention is being paid to the mathematical constraints required for justifiable application of the theory. One gets the impression that some previous applications have been forced into the catastrophe theory mold. Lewis (1977) is investigating several correlation and regression procedures that can indicate the existence and location of a cusp or butterfly catastrophe. This kind of approach allows the investigator to see if his data is appropriate for description by catastrophe theory rather than having him force data which may not be appropriate into such a framework.

3. Summary and Conclusions:

Perhaps the best summary of the state of applications of Catastrophe
Theory to practical problems is made by Thom from a vantage point 5 years
after his book Stabilite Structurelle et Morphogénèse (Thom, 1972) was published. "... C.T. (Catastrophe Theory) arose from mathematics, and it has
led to important progress in mathematics itself ... On the contrary, the
'practical' results of C.T. are, up to now, not very striking; evaluated by
the strict-positivist-criterion of the discovery of 'new phenomena', they reduce to a few (not too surprising) facts in geometric optics elaborated by
M. Berry at Bristol in his work on caustics" (p. 189-100).

"From my viewpoint, C.T. is fundamentally qualitative and has as its fundamental aim the explanation of an empirical morphology. Its epistomological status is the one of an interpretive-hermeneutic theory. Hence it is not obvious that it will necessarily develop into new pragmatic developments" (p. 193).

This, in fact, is our conclusion. At present, catastrophe theory may be able to provide a description (usually visual) which may help one comprehend the way known data interact, but is seems very unlikely that the theory can now make the quantative prediction we require of a metric for human performance. The state of the art is clearly shown by the recent lecture given by Zeeman at the UCLA Mathematics Colloquium (Nov.1977). After showing the beautiful way the stability of ocean-going vessles could be described by a cusp catastrophe, we were all waiting for him to make the jump to the next step, to tell us what new insights had been gained from the model. At that point he said, "I'm not sure just what to do next ...".

FOOTNOTES

 All use of human subjects is in compliance with the requirements of the UCLA Human Subject Protection Committee regulation and Air Force human use regulations (Consent of Volunteer Form, Experimental Control No. OSR 77-3184).

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TABLE I

	Targets	Drones	Total # Items	Ratio (Targets to Drones)
Experiment I	1	1	2	1/1
	2	2	4	1/1
	3	3	6	1/1
	6	6	12	1/1
	9	9	18	1/1
	1	3	4	1/3
	2 .	6	8	1/3
	3	9	12	1/3
	1	5	6	1/5
	2	10	12	1/5
	3	15	18	1/5
Experiment II	1	1	2	1/1
	1	3	4	1/3
	1	5	6	1/5
	1	7	8	1/7
	1	11	12	1/11
	1	15	16	1/15

FIGURE CAPTIONS

- 1. Target (top) and drone (bottom) elements for clutter display.
- 2. a-h Photograph of a scenario starting about 5 sec after the start of the trial. The pictures were taken approximately 5 sec apart. Figure 1h shows the 9 targets diving toward the observer. The light images on either side of the main group of targets are afterimage generated by the rapid movement of the objects across the graphics screen.
- 3. Exp. I. a) LAT 1 as a function of target-drone ratio.
 - b) LAT 1 as a function of total number of elements (targets & drones).
- 4. Exp. I. a) LAT 2 as a function of target-drone ratio.
 - b) LAT 2 as a function of total number of elements (targets & drones)
- 5. Exp. I. Mean distance of selected target (-) and mean distance of all targets (---) as a function of target-drone ratio.
- 6. Exp. I. Mean distance of selected target (-) and mean distance of all targets (---) as a function of total number of elements (targets & drones).
- 7. Exp. I. a) LAT 1 for 1 target as a function of total number of elements (targets-drones).
 - b) LAT 2 for 1 target as a function of total number of elements.
 - c) Mean target distance as a function of total number of elements.
- 8. Exp. II. a) LAT 1 as a function of total number of elements (targets & drones).
 - b) LAT 2 as a function of total number of elements.
 - c) Mean target distances as a function of total number of elements.

- 9. a-g Elementary catastrophe theory surfaces and projections. (a) fold, (b) cusp,
 (c) swallowtail, (d) hyperbolic umbilic, (e) elliptic umbilic, (f) butterfly,
 (g) parabolic umbolic. See text for further details (from Scientific America,
 1976 (4)).
- 10. Example of a cusp catastrophe describing a dog's behavior resulting from changes in fear and rage. See text for details (from Scientific America, 1976 (4)).
- 11. Example of a cusp catastrophe describing the buckling of a beam under load and compression forces. See text for details (from Scientific America, 1976 (4)).

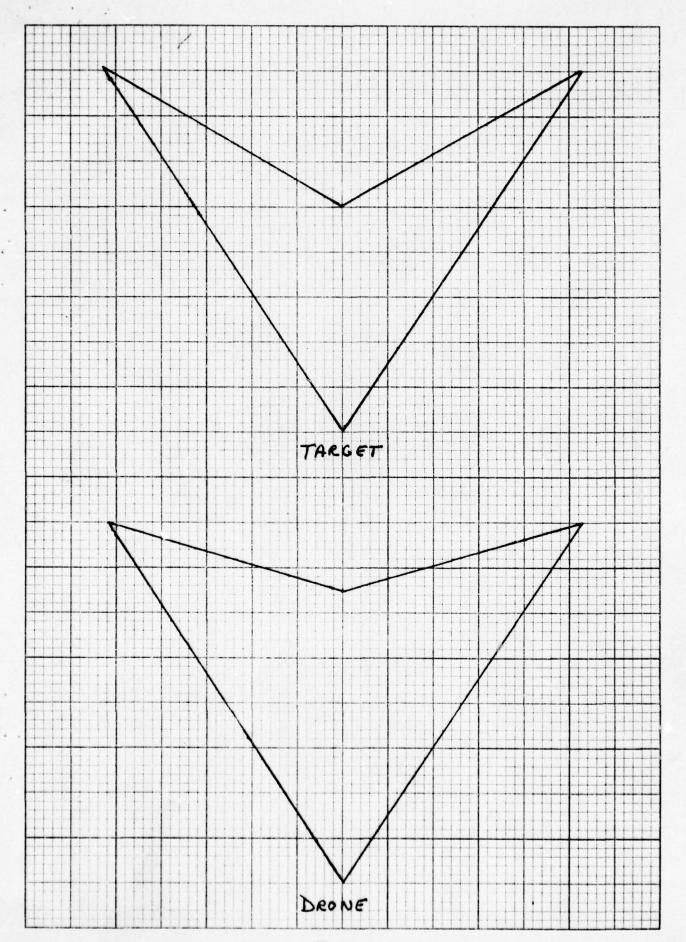
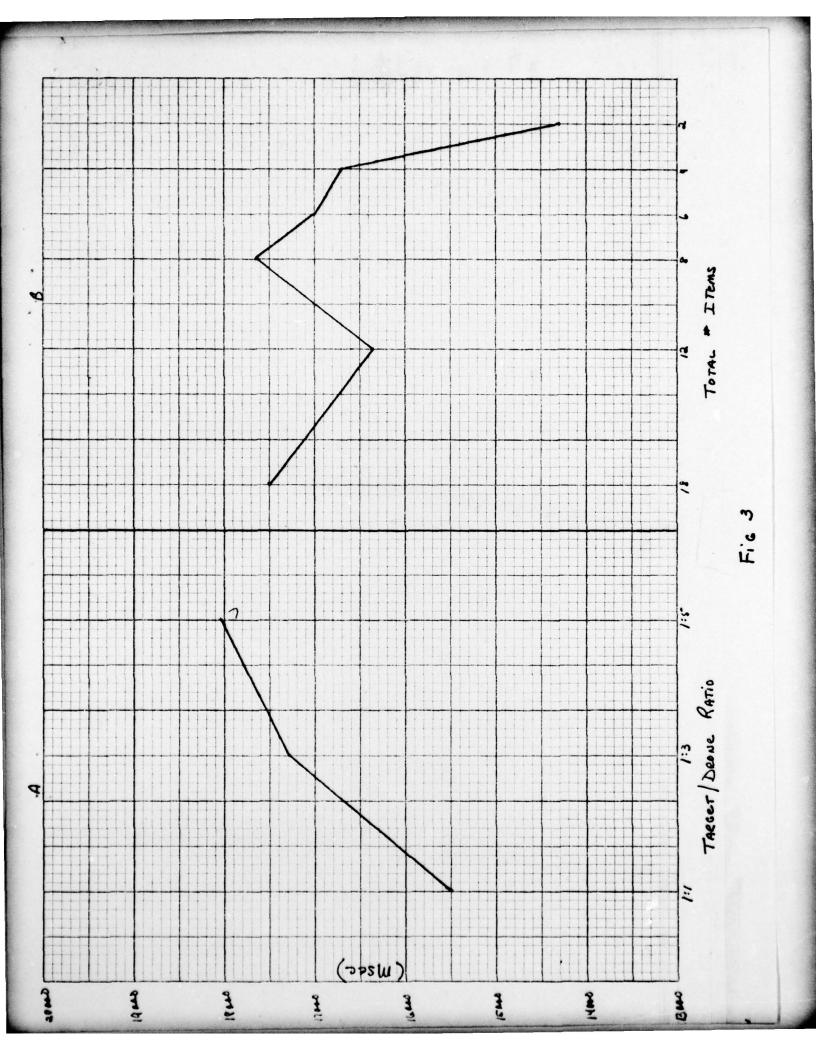
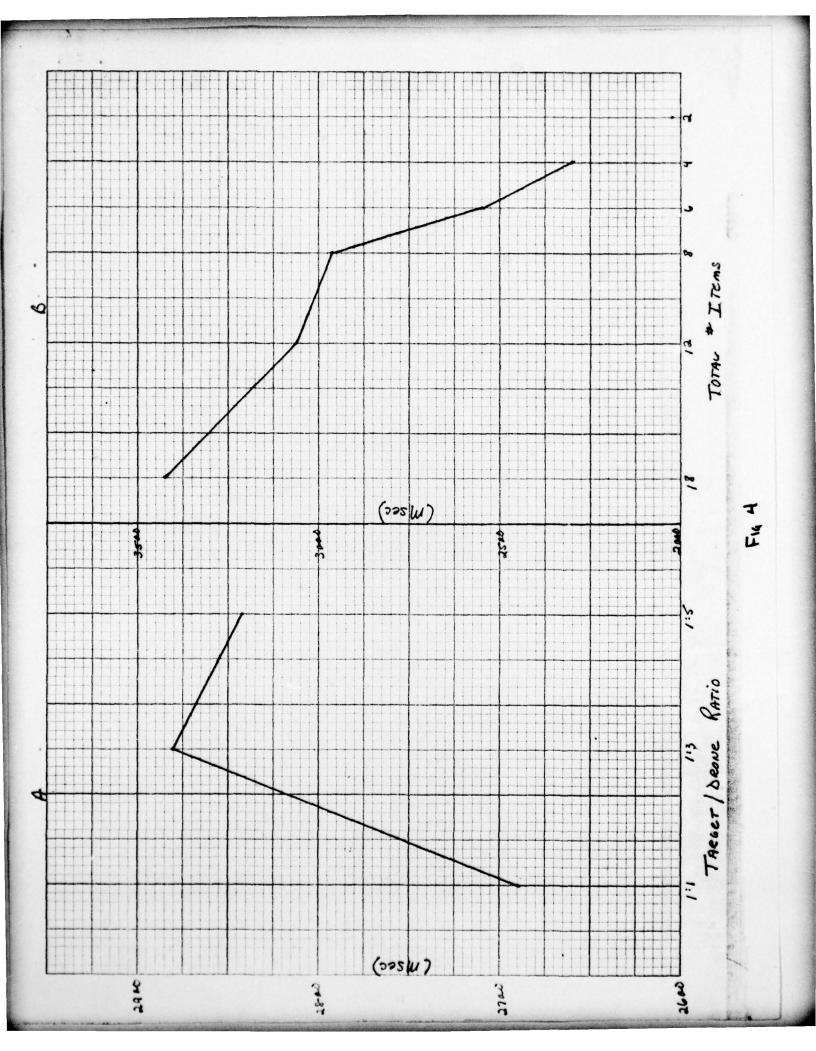


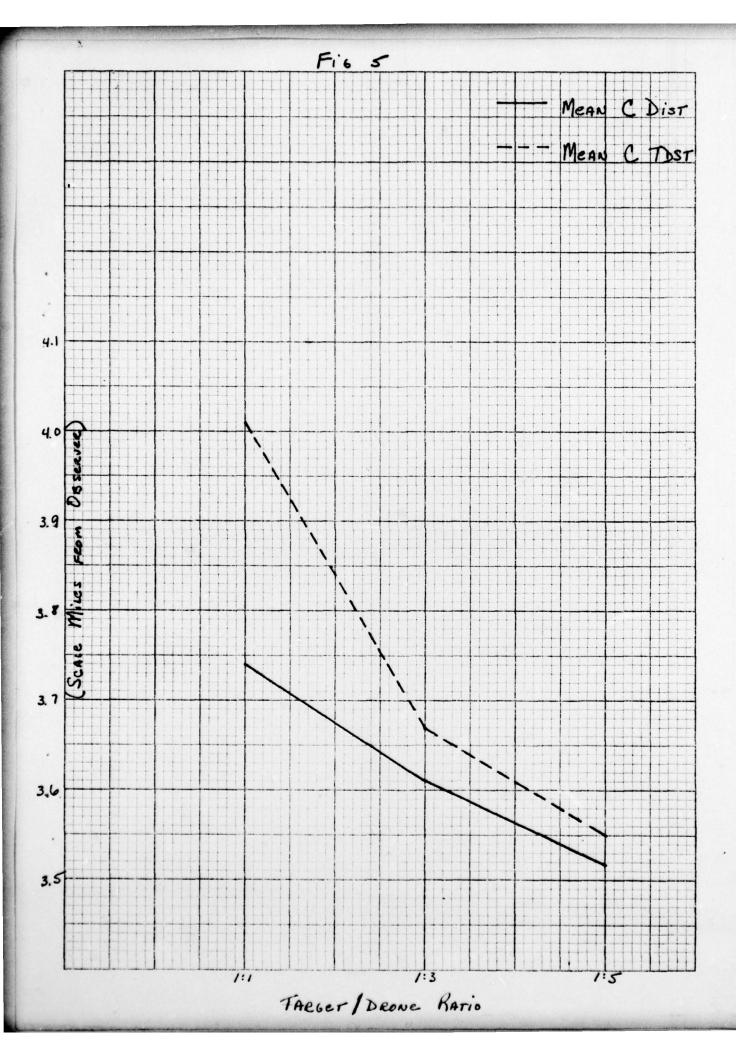
Fig 1

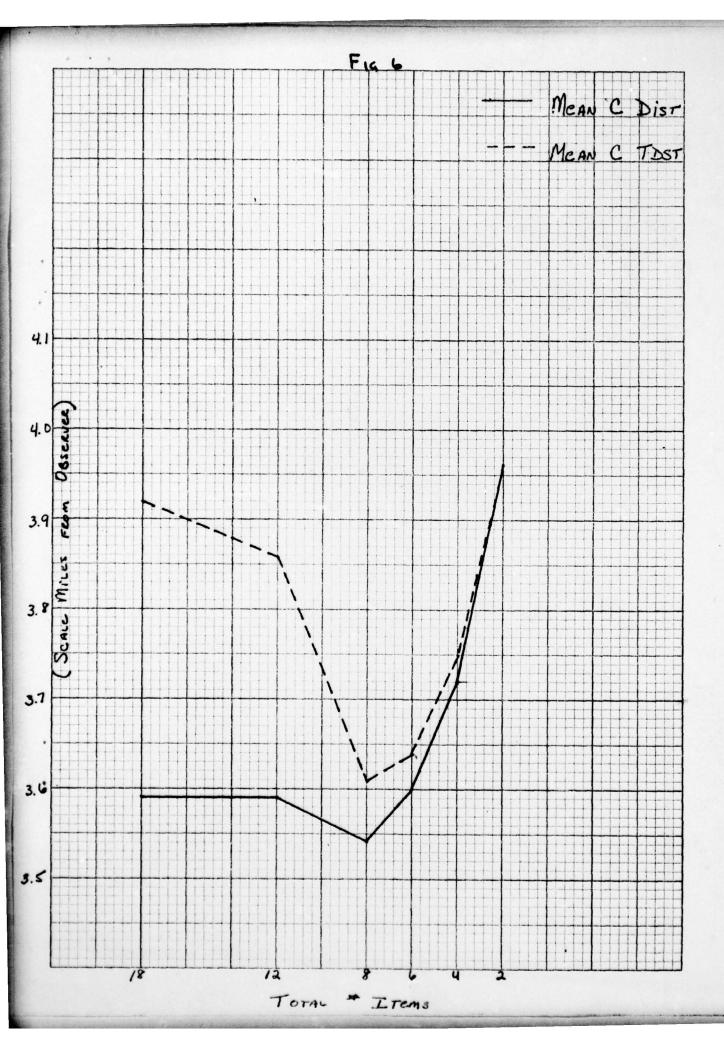
Fic 2-F

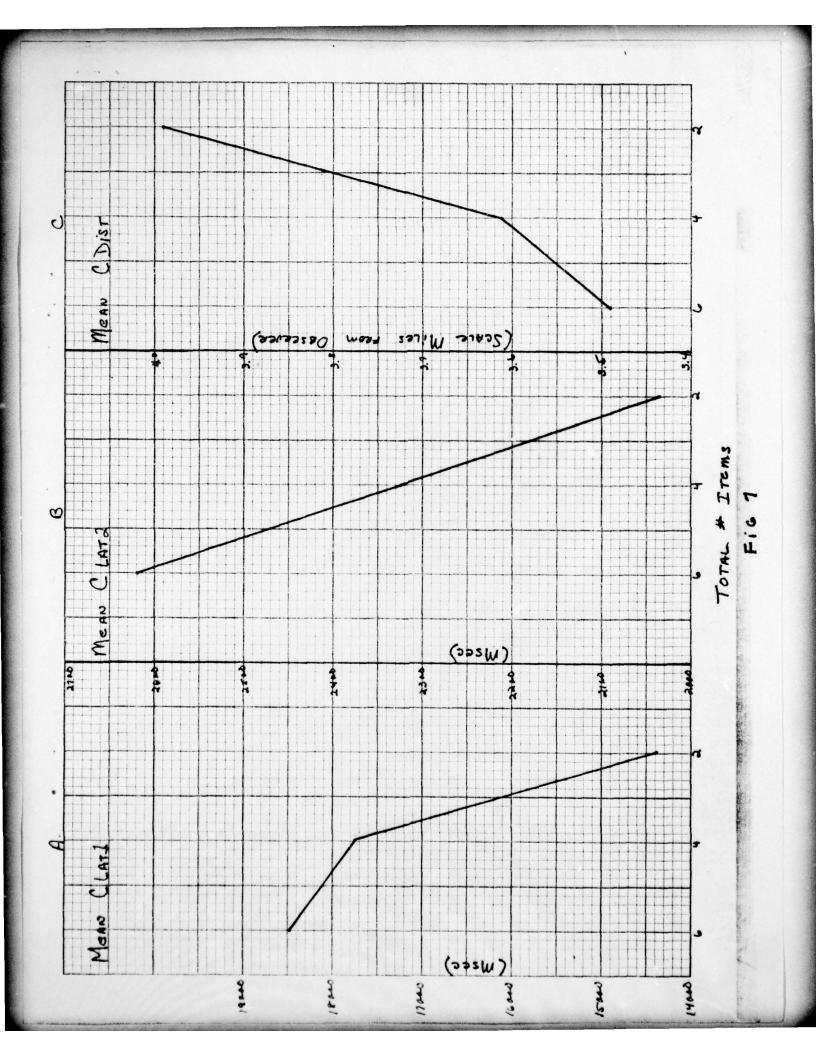
Fig 2-H

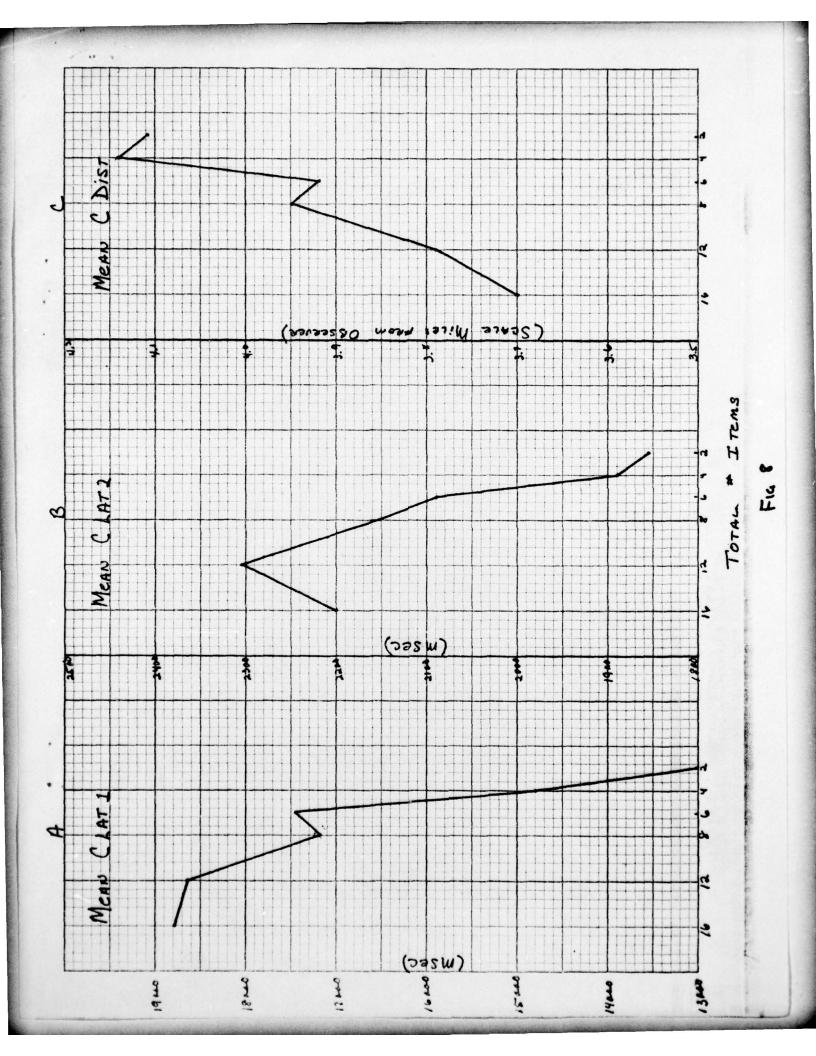






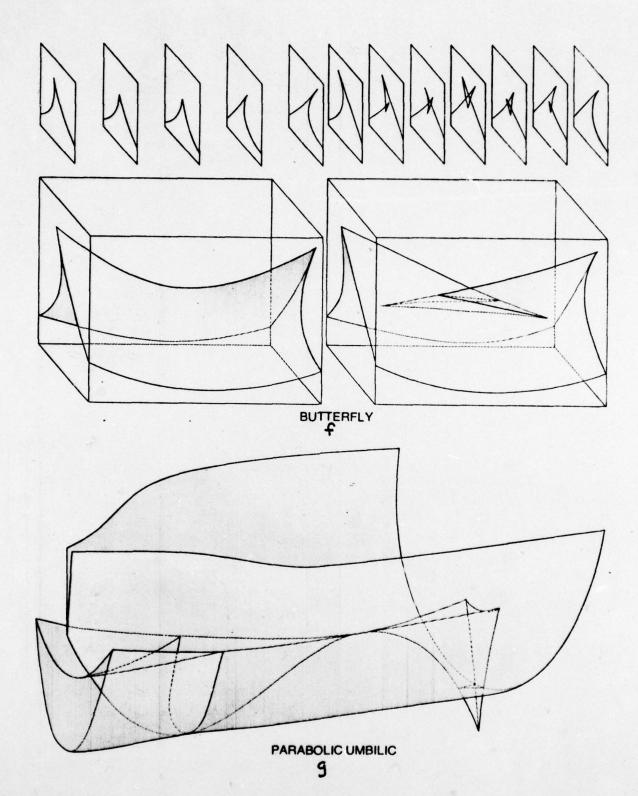






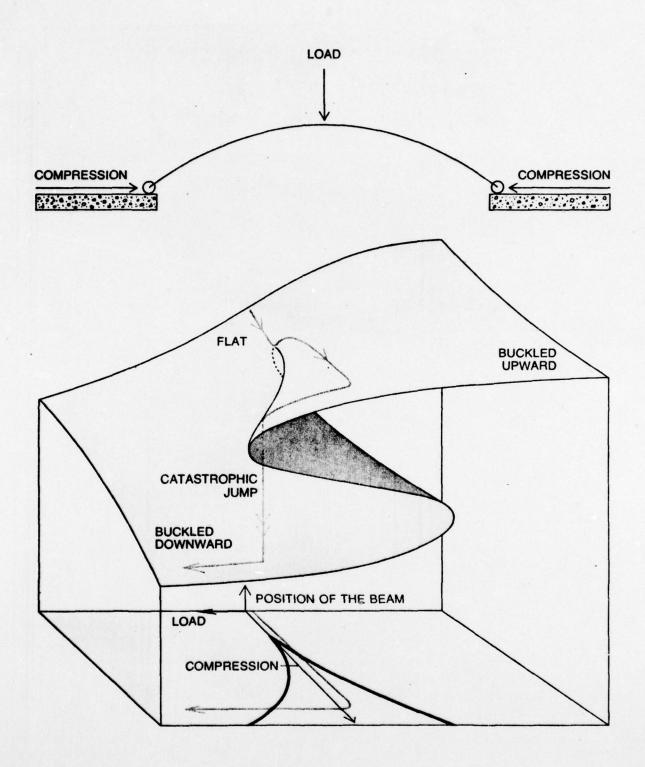
BEHAVIOR

F14 9



Fic 9

Fic 10



F14 11

UNCLASSIFIED SECURITY CLASSIFICATION OF THIS PAGE (When Date Entered) **READ INSTRUCTIONS** AREPORT DOCUMENTATION PAGE BEFORE COMPLETING FORM 3. RECIPIENT'S CATALOG NUMBER 2. GOVT ACCESSION NO. Development of Neurophysiological and Behavioral 30 Sep Metrics of Human Performance PERFORMING ORG. REPORT NUMBER 8. CONTRACT OR GRANT NUMBER(s) 7. AUTHOR(a) Moise, Jr AFOSR-77-3184 Samuel L. 9. PERFORMING ORGANIZATION NAME AND ADDRESS PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT HUMBERS University of California, Los Angeles Brain Research Institute Los Angeles, California 90024 11. CONTROLLING OFFICE NAME AND ADDRESS 12. REPORT DATE Air Force Office of Scientific Research (NL) Nov 30, 1977 11 Bolling AFB, DC 20332 13. NUMBER OF PAGE 59 14. MONITORING AGENCY NAME & ADDRESS(II different from Controlling Office) SECURITY CLASS. (UNCLASSIFIED DECLASSIFICATION/DOWNGRADING 16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, If different from Report) 18. SUPPLEMENTARY NOTES 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Clutter, Performance, Electrophysiology, Visual Evoked Response, Catastrophe Theory 20. ABSTRACT (Continue on reverse side if necessary and identify by block nu The purpose of this program of research is to develop metrics derived from multidimensional behavioral and neurophysiological indices which may ultimately be applied across a wide range of tasks to describe and predict human performance. This year's effort represented two different approaches to this problem: the development of a methodology for examining clutter factors that affect target identification, and the evaluation of Catastrophe Theory as a potential metric for describing discontinuities in human behavior. (Continued on reverse side)

A

A comprehensive software/hardware package for examining clutter variables in the laboratory was assembled and its utility demonstrated by a major experiment examining the effect on performance of number of clutter objects and target/drone mix. Initial analysis of the behavioral data has been computed and is reported here. Detailed analysis of the electroencephalographic data is in progress. It is clear that the system provides a powerful, flexible tool for study of visual clutter.

A large representative bibliography of application of Catastrophe Theory has been compiled and is part of this report. Evaluation of the usefulness of Catastrophe Theory as a metric for predicting human performance is clear at this time. The theory allows qualitative construction of models which reflect the behavior of systems in which discontinuities are observed, but at present does not allow quantative, predictive modeling of such systems. At present, then, Catastrophe Theory would not seem to be suitable for generating predictive metrics of human performance.